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Removal of cattle manure constituents in runoff from no-till cropland as affected by setback distance

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REMOVAL OF CATTLE MANURE CONSTITUENTS IN RUNOFF FROM NO-TILL CROPLAND AS AFFECTED BY SETBACK DISTANCE

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ABSTRACT. *Vegetative filter strips located at the bottom of a hillslope have been shown to substantially reduce nutrients and sediment in runoff. Cropland areas could serve a similar function. However, little scientifically derived information is available to help identify the setback distances required to effectively reduce the transport of contaminants in runoff. The objective of this study was to determine the effects of setback distance and runoff rate on the concentrations and mass transport rates of selected constituents following land application of beef cattle manure to a no-till cropland area. The study site had a residue cover of 8.84 Mg ha^{-1} and a slope gradient of 6.2%. The 20 plots examined during the investigation were 3.7 m across the slope by 4.9, 7.9, 11.0, 17.1, or 23.2 m long. An initial set of rainfall simulation tests were completed to determine background concentrations and mass transport rates of selected constituents. Cattle manure was then applied to the upper 4.9 m of each plot, and additional rainfall simulation tests were conducted. A first-order exponential decay function was used to estimate the effects of setback distance on the concentrations and mass transport rates in runoff. A setback distance of 12.2 m effectively reduced the concentrations of DP, TP, NH_4-N, boron, calcium, magnesium, potassium, and sulfate and the mass transport rates of DP, TP, NH_4-N, boron, and potassium to background values similar to those measured on the no-manure treatment. Runoff rate was an important variable influencing each the measured constituents, with mass transport rates increasing as runoff rate increased.*

Keywords. *Cattle manure, Filter strips, Land application, Manure management, Manure runoff, Nitrogen, Nutrients, Phosphorus, Runoff, Water quality.*

Animal manures serve as a valuable nutrient source for crop production. Decreasing crop production costs by replacing a portion of mineral fertilizer with manure nutrients is an important economic strategy that can also improve soil fertility. However, application of manure on cropland areas can result in off-site environmental concerns, especially if applied near environmentally sensitive areas like stream banks or hydraulic conduits to surface water or groundwater.

Setbacks are the prescribed distances from surface waters, open tile intake structures, well heads, and other conduits to surface water and groundwater within which manure application is not allowed. At least 34 states have established setback distance requirements for land application areas. The U.S. Environmental Protection Agency has also instituted setback distances for land application of manures with National Pollutant Discharge Elimination System permits. However, little scientifically derived information is available to help identify the setback distances needed to effectively reduce contaminants in incoming runoff from cropland areas.

Conservation buffers are small areas of land in permanent vegetation that serve to intercept pollutants. Vegetative filter strips (VFS) are a type of conservation buffer that has been effectively used on cropland areas. The establishment of VFS at the bottom of a hillslope is a conservation practice that has been shown to substantially reduce nutrients and sediment in runoff (Dillaha et al., 1989; Magette et al., 1989; Coyne et al., 1995). VFS are usually established using perennial grasses. The effectiveness of VFS is influenced by runoff rate, width of the vegetative filter, and characteristics of the runoff area (Bingham et al., 1980; Daniels and Gilliam, 1996; and Robinson et al, 1996).

Chaubey et al. (1995a), Srivastava et al. (1996), and Lim et al. (1998) examined the effects of VFS width on the concentrations and transport of nutrients in runoff from fescue plots treated with manure. The VFS significantly reduced the concentrations and mass transport of incoming constituents. The relationships among VFS width, concentration, and mass transport were well-represented by first-order exponential decay functions.

Setback areas containing crop residue and/or actively

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growing vegetation where manure has not been applied could serve a function similar to VFS. Previous field experiments that examined the effectiveness of VFS in reducing the transport of constituents in incoming runoff could provide insight concerning the removal of manure constituents in runoff from cropland areas. The first-order exponential decay functions among VFS width, concentration, and mass transport may also have application for cropland areas. The objective of this study was to determine the effects of manure application, setback distance, and runoff rate on the concentrations and mass transport rates of selected constituents following land application of beef cattle manure to a no-till cropland site.

SETBACK DISTANCE DESIGN CONSIDERATIONS

Edwards et al. (1996a) reported that runoff water quality studies involving fertilizers applied to grassed areas suggest that VFS can be designed by assuming that (1) only infiltration is responsible for pollutant removal, (2) the first post-application runoff event is most important from a water quality perspective, and (3) no pollutant build-up that degrades VFS performance will occur. They developed a VFS design algorithm for grassed areas that used the Soil Conservation Service (SCS, 1972) curve number method for runoff estimation and the Overcash et al. (1981) equation for predicting concentrations of pollutants exiting a VFS as a function of VFS and runoff parameters. The algorithm can be used to determine the VFS width required to meet an allowable pollutant runoff concentration or pollutant mass transport. Alternately, the algorithm can also be used to determine the VFS width required to achieve given relative reductions in incoming pollutant runoff concentrations and mass transport. Roberts et al. (2012) found evidence of a surface layer in vegetated buffer strip soils that is enriched in soluble P that may be responsible for increased dissolved phosphorus (DP) delivery.

Srivastava et al. (1998) validated an event-based nutrient transport model (Chaubey et al., 1995b) that simulates soluble nutrient transport in VFS. The model linked three submodels: modified Green-Ampt infiltration, non-linear kinematic overland flow routing, and a nutrient transport component. The results indicated that accurate prediction of infiltration and runoff was critical for reliable estimation of nutrient concentrations and mass transport. Infiltration is thought to be the principal mechanism responsible for pollutant removal in VFS. If accurate estimates of infiltration and runoff can be made for cropland areas, the equations, algorithms, and models developed for VFS may also be applied to determine appropriate setback distances on cropland areas. Parameterization of predictive relationships for cropland areas may require collection of additional field data.

Important factors influencing infiltration on cropland areas are (1) soil physical and chemical characteristics, (2) vegetative cover, and (3) slope gradient. Dosskey et al. (2008) developed a graphical design aid for determining the width of VFS by considering field length, slope, soil texture, and cover management. Raindrop impact on cropland areas that are not covered by crop residue may result in surface sealing and greatly reduced infiltration rates. Extensive residue cover, such as that found on no-till or minimum-till cropland areas, serves to protect the soil surface from raindrop impact and enhance infiltration. The perennial grasses present within VFS usually result in relatively large infiltration rates. As a result, the distances required to remove pollutants in runoff from VFS may be less than those necessary on cropland areas.

It is assumed that runoff occurs as overland flow on both VFS and cropland areas. Overland flow runoff velocities are reduced when substantial vegetation (VFS) or crop residue is present, which allows increased opportunity for infiltration. If concentrated flow or rilling occurs, the effectiveness of VFS or cropland areas in reducing contaminant transport is substantially reduced.

MATERIALS AND METHODS

STUDY SITE CHARACTERISTICS

This field study was conducted at the University of Nebraska Rogers Memorial Farm located 18 km east of Lincoln, Nebraska. The study site had been cropped using a long-term no-till management system with controlled wheel traffic, which included a soybean, winter wheat, soybean, grain sorghum rotation. Winter wheat was harvested on 10 July 2014. A mixture of legumes (sunn hemp, spring forage peas, and chickling vetch), grasses (sorghum sudan, pearl millet, and oats) brassicas (ethopian cabbage and rapeseed), and other broadleaves (flax and buckwheat) was seeded as a cover crop on 24 July 2014. The seed mixture was selected so the cover crop would be killed by freezing temperatures over the winter. Since there were no weeds present, it was not necessary to apply herbicide prior to planting the cover crop. Glyphosate was applied in May 2015 to control weed growth at the study location. The amount of vegetative material at the study site at the time of the field tests was 8.83 Mg ha^{-1}.

Runoff water quality is influenced by soil characteristics near the surface. As a result, soil samples for study site characterization were obtained from the surface to 2 cm depth from selected locations. The soil at the site developed in loess under prairie vegetation and is considered a benchmark soil for the western Corn Belt. Using procedures for soil particle size determination reported by Kettler et al. (2001), the Aksarben silty clay loam (fine, smectitic, mesic Typic Argiudoll) was found to contain 19% sand, 46% silt, and 35% clay. The saturated hydraulic conductivity of the Aksarben soil is moderately low, and the soil belongs to hydrologic group C.

Mean concentrations of Bray and Kurtz No. 1 P (Bray and Kurtz, 1945), water-soluble P (Murphy and Riley, 1962), and NO_3-N and NH_4-N in the soil measured with a flow injection analyzer using spectrophotometry (AutoAnalyzer 3, SEAL Analytic Inc., Mequon, Wisc.) were 106, 17, 20, and 5 mg kg^{-1}, respectively. The study site had a mean slope gradient of 6.2% (standard deviation of 1.2%), an electrical conductivity (EC) of 0.48 dS m^{-1}, and a pH of 7.0 (Klute, 1986). Using laboratory procedures developed by Nelson and Sommers (1996), the organic matter and total carbon content of the soil were 50 and 26 g kg^{-1}, respectively, which are relatively high for cropland sites in this area.

EXPERIMENTAL DESIGN

The experimental plots were established using a randomized block design. Plots 101 to 110 were contained in block 1, while block 2 consisted of plots 201 to 210 (fig. 1). The nature of the rainfall simulation equipment dictated that paired plots be used. Experimental treatments included manure application or no manure application, setback distance, and inflow rate. The plots were 3.7 m wide across the slope with lengths of 4.9, 7.9, 11.0, 17.1, or 23.2 m. Inorganic fertilizer was not applied at any time during the investigation.

Rainfall simulation tests on plots with a given length were first conducted without manure. After the investigations with no manure were completed, manure was applied to the upper 4.9 m of the plots, and additional rainfall simulation tests were conducted. Experimental tests conducted by Srivastava et al. (1996) and Edwards et al. (1996b) indicated that a manure treatment length of 3.0 m was sufficient to simulate runoff quality associated with longer manure treatments. Field tests were performed in the present investigation on two plots belonging to the same treatment each week during a ten-week test period (20 plots total) beginning on 1 June 2015 and ending on 7 August 2015.

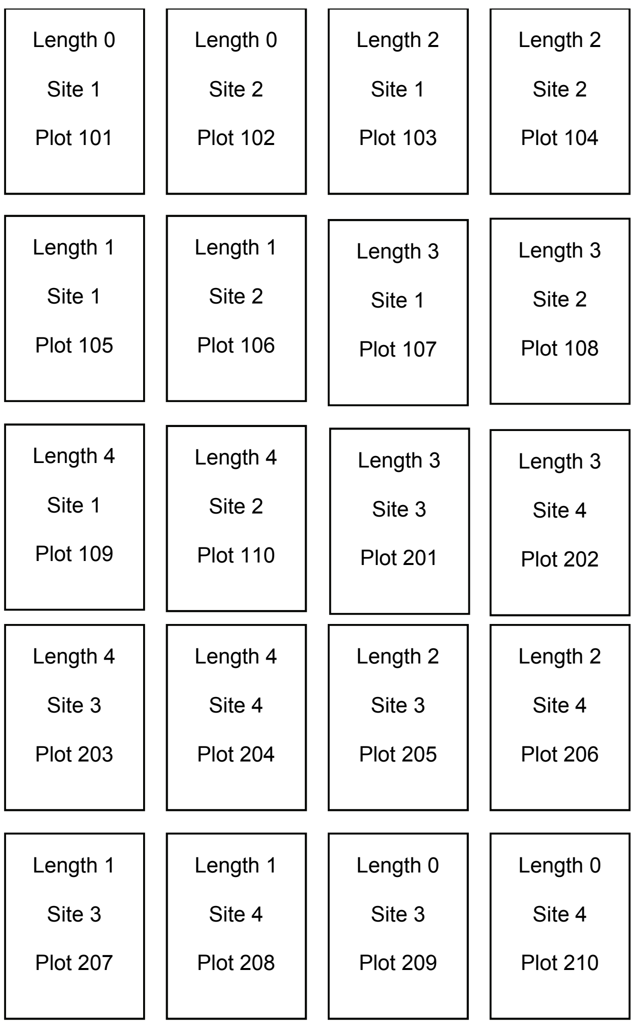

Figure 1. Schematic showing the layout of the experimental plots. Plot lengths of 0, 1, 2, 3, and 4 correspond to total plot distances of 4.9, 7.9, 11.0, 17.1, and 23.2 m, respectively. Manure was applied to the upper 4.9 m of each plot after the tests with no manure were completed.

Single grab samples for water quality analyses were collected under steady-state runoff conditions. Recent rainfall simulation protocols require that the plots on which rainfall simulation tests are conducted be saturated before runoff sample collection begins (Allen and Mallarino, 2008; Verbree et al., 2010). Pre-saturation of the plots helps to minimize the effects of varying antecedent soil moisture conditions. If the plots are pre-saturated, then steady-state conditions are established in a short period of time once simulated rainfall is applied. The collection of runoff samples under steady-state conditions in this investigation served to minimize the effects of varying antecedent soil moisture content. The field experimental and analytical procedures used in the present investigation for no-till cropland areas were developed from studies on VFS conducted by Chaubey et al. (1995a), Srivastava et al. (1996), Lim et al. (1998), and Edwards et al. (1996b).

Lim et al. (1998) used the following first-order exponential decay model to relate runoff concentration (C, mg L^{-1}) to VFS width (x, m):

$$C(x) = C_0 \cdot e^{-kx} \quad (1)$$

where C_0 is a coefficient, and k is the rate coefficient (m^{-1}). The coefficient C_0 would be equal to the runoff concentration for a setback distance length of 0 m for data that are described perfectly by equation 1. However, the coefficients C_0 and k were determined through regression analysis, and C_0 was not constrained to be equal to the concentration at the 0 m setback distance.

The following first-order exponential decay model was used by Lim et al. (1998) to relate mass transport rate (T, kg ha^{-1} min^{-1}) to vegetative filter width (x, m):

$$T(x) = T_0 \cdot e^{-nx} \quad (2)$$

where T_0 is a coefficient, and n is a rate coefficient (m^{-1}). The coefficient T_0 would be equal to the mass transport rate for a setback distance of 0 m for data that are described perfectly by equation 2. However, the coefficients T_0 and n were determined through regression analysis, and T_0 was not constrained to be equal to the mass transport rate at the 0 m setback distance.

MANURE COLLECTION AND APPLICATION

The beef cattle manure used in this study was obtained from a manure stockpile located at the U.S. Meat Animal Research Center (MARC) near Clay Center, Nebraska. The stockpiled manure was recently removed from feedlot pens where cattle were fed a corn-based diet. The manure was collected and transported in 20 L plastic buckets until it was applied. A subsample of the manure was obtained for chemical and physical analyses, which were performed at a commercial laboratory. Mean measured values of NO_3-N, NH_4-N, total N (TN), total phosphorus (TP), calcium, magnesium, potassium, sodium, water content, EC, and pH for the manure on a dry basis were <0.01 g kg^{-1}, 0.12 g kg^{-1}, 14.4 g kg^{-1}, 6.9 g kg^{-1}, 27.3 g kg^{-1}, 7.4 g kg^{-1}, 20.7 g kg^{-1} 2.3 g kg^{-1}, 436 g kg^{-1}, 22.6 dS m^{-1}, and 8.8, respectively. Manure was applied at an amount required to meet the annual N requirement for corn (151 kg N ha^{-1} $year^{-1}$ for an expected yield of 9.4 Mg ha^{-1}). When calculating manure application rate, it was assumed that the N availability from beef cattle manure was 40% of the total amount of measured N (Eghball et al., 2002). The manure was broadcast by hand to the soil surface, with care taken to ensure uniform distribution. The manure was not incorporated following application.

Rainfall Simulation Procedures

A portable rainfall simulator designed by Schulz and Yevjevich (1970) was used to apply rainfall at a rate of approximately 52 mm h^{-1}. A relatively wide range of intensities have been used in rainfall simulator design. The rainfall intensity of the simulator used in this investigation falls in the lower range used for field testing. The "sprinkler head grid system" used 3 m sections of 10 cm diameter irrigation pipe on which 2 cm diameter risers were mounted. Sprinkler heads were located on the top of the risers, which also contained a globe valve, a flow control valve, and a screen. The rainfall simulator was assembled in a modular fashion to accommodate plots with variable lengths. Rain gauges were placed along the outer edge of each plot to monitor rainfall intensity.

Water used in the rainfall simulation and inflow tests was obtained from an irrigation well. Measured mean concentrations of DP, total phosphorus (TP), NO_3-N, NH_4-N, and total nitrogen (TN) in the irrigation water were 0.16, 0.16, 15.8, <0.1 and 15.8 mg L^{-1}, respectively. The irrigation water had a mean EC of 0.78 dS m^{-1} and a pH of 7.7.

Plot borders consisted of 3 m long sections of sheet metal that diverted runoff into a collection trough. The collection trough discharged into a flume where a stage recorder was mounted to measure flow rate. Single grab samples for water quality and sediment analyses were obtained once steady-state runoff conditions were indicated by the stage recorder and flume. Runoff samples for water quality analyses were kept in a cooler containing ice packs until arrival at the laboratory.

An initial rainfall simulation run without manure addition occurred at existing soil-water conditions and continued until steady-state runoff conditions had become established. A second rainfall simulation run was then conducted approximately 24 h later, and it also continued until steady-state runoff conditions occurred. Laboratory results obtained from runoff samples collected during each of the two rainfall simulation runs were included in the statistical analyses.

Soon after completion of the second rainfall simulation run, additional field tests were conducted to identify the effects of varying runoff rates on nutrient transport. Water was added to the test plots to simulate increased runoff rates resulting from larger upslope contributing areas. Rainfall continued to be applied during the inflow tests. The addition of inflow to test plots to simulate greater slope lengths is a well-established experimental procedure (Monke et al., 1977; Laflen et al., 1991; Misra et al., 1996).

A mean overland flow rate of 25.6 L min^{-1} was measured without the addition of inflow. Inflow was applied at the upgradient end of the plot while rainfall application continued at a rate of approximately 52 mm h^{-1}. Inflow was added in three successive increments to produce average runoff rates of 49.4, 64.3, and 87.6 L min^{-1}. A narrow mat made of green synthetic material, often used as outdoor carpet, was placed on the soil surface beneath the inflow device to prevent scouring and distribute the flow more uniformly across the plot surface.

Runoff was diverted into a flume where a stage recorder was mounted to measure flow rate. Flow addition for each simulated overland flow increment occurred only after steady-state runoff conditions for the previous increment were reached and samples for water quality and sediment analyses had been collected. Each simulated overland flow increment was maintained for approximately 8 min. After runoff samples for water quality and sediment analysis were obtained, the rate of inflow into the plot was increased and additional runoff samples were collected after steady-state runoff conditions were reestablished. The units used to report mass transport rates were kg ha^{-1} min^{-1}. When calculating mass transport rates, concentration measurements (mg L^{-1}) were multiplied by flow rates (L min^{-1}), and the result was divided by the total plot area (ha^{-1}).

Manure was applied to the upper 4.9 m of the paired plots on day 3 of the weekly test regime, and rainfall simulation tests continued on the same day manure was applied until steady-state runoff conditions were established. Additional rainfall simulation tests occurred approximately 24 h later, again until establishment of steady-state runoff conditions. Tests using added inflow were continued using the previously described procedures.

Runoff samples were analyzed for DP after being centrifuged and filtered with filter paper having a porosity of <11 μm (Murphy and Riley, 1962). Values for DP reported in this investigation are the difference between laboratory measurements and background values obtained for the irrigation water. Samples that were not centrifuged were analyzed in a commercial laboratory for total phosphorus (TP) (Johnson and Ulrich, 1959), NO_3-N, NH_4-N, TN, (Tate, 1994), boron, calcium, chloride, magnesium, potassium, sodium, sulfate, EC, and pH. The reported concentration values represent laboratory measurements of the individual grab samples and not flow-weighted mean concentrations.

Runoff samples were also collected under steady-state conditions for sediment analysis. The total mass of the plastic bottles used for sediment analyses was first measured. Tare weights of the bottles had been previously obtained. The plastic bottles were then dried in an oven at 105°C and weighed again to determine the remaining mass of sediment (total solids). The sediment content of the runoff samples was determined by calculating the mass of material remaining in the bottles after drying divided by the mass of water contained in the bottles before drying (the total measured mass of liquid minus the mass of total solids). The mass of dissolved chemical constituents contained in the runoff was assumed to be negligible.

Statistical Analyses

Separate statistical analyses were performed for the water quality measurements and mass transport values. Manure application (manure or no manure), setback distance (0, 3.0, 6.1, 12.2, and 18.3 m), and flow rate (25.6, 49.4, 64.3, and

87.6 L min^{-1}) were the treatment factors. It was necessary to perform a log-transform of the response variables to satisfy statistical assumptions. Analysis of variance was performed using the GLIMMIX procedure of SAS (2011) to determine the effects of manure application, setback distance, and inflow rate on water quality measurements and mass transport rates. If a significant difference was identified, the least significant difference (LSD) test was used to identify differences among experimental treatments. A probability level $p \leq 0.05$ was considered significant.

RESULTS AND DISCUSSION

RUNOFF CHARACTERISTICS

Concentration Measurements

An interaction in concentration measurements between manure application and setback distance was found for each of the constituents except NO_3-N, chloride, and sediment content (table 1). The effects of setback distance on concentrations of DP, ammonium, potassium, and sodium for both the manure and no-manure conditions are shown figures 2, 3, 4, and 5, respectively. For each of the water quality constituents for which interaction effects were identified, changes in constituent concentration, in general, were minimal among setback distances on the treatments with no manure. In contrast, significant reductions in concentration values were found among setback distances on the plots with manure, with concentration values, in general, decreasing as setback distance increased (table 1). As an example, concentrations of DP on the treatments containing manure decreased by 79% as setback distance increased from 0 to 12.2 m (fig. 2). For each of the chemical constituents except sodium, a setback distance of 12.2 m effectively removed constituents in runoff to values similar to those obtained on the no-manure treatments. The concentrations of sodium measured at the 12.2 m setback distance on the plots with manure were significantly less than the values obtained at the 18.3 m length (fig. 5). However, sodium concentrations on the plots where manure was applied were significantly greater than values obtained at corresponding lengths on the plots with no manure.

The 19.2 mg L^{-1} of NO_3-N in runoff measured on the no-manure treatment was significantly greater than the 16.1 mg L^{-1} obtained on the plots containing manure (table 1). After

Table 1. Effects of manure application and setback distance on water quality parameters averaged over two rainfall simulation runs.[a]

	DP	TP	NO_3-N	NH_4-N	TN	Boron	Calcium	Chloride	Magnesium	Potassium	Sodium	Sulfate	EC	pH	Sediment Content
Manure application															
No manure	0.777 b	0.851 b	19.2 a	0.237 b	24.4	0.047 b	69.5 b	4.4 b	16.6 b	17.1 b	41.9 b	15.7 b	0.683 b	7.76 b	0.104
Manure	1.44 a	2.04 a	16.1 b	1.06 a	26.3	0.083 a	77.8 a	11.0 a	19.3 a	33.6 a	62.3 a	21.4 a	0.884 a	7.97 a	0.112
Setback distance (m)															
0.0	1.78 a	2.57 a	18.3	1.40 a	30.0 a	0.111 a	71.4 b	10.9 a	19.3 a	45.8 a	61.3 a	22.5 a	0.882 a	7.96 a	0.184 a
3.0	1.04 b	1.35 b	17.4	0.872 b	26.0 b	0.083 b	79.6 a	8.4 a	18.8 a	26.1 b	54.2 b	20.2 b	0.836 ab	7.87 b	0.138 ab
6.1	0.937 b	1.18 b	17.2	0.543 c	24.5 b	0.064 c	77.7 a	7.5 a	18.8 a	23.6 b	53.7 b	18.1 c	0.795 b	7.88 b	0.119 bc
12.2	0.865 b	0.955 b	16.9	0.233 d	23.1 b	0.034 e	71.3 b	3.6 b	16.3 b	15.9 c	46.3 c	16.1 d	0.720 c	7.89 b	0.084 cd
18.3	0.875 b	1.01 b	18.4	0.203 d	23.5 b	0.047 d	68.2 b	6.5 ab	16.3 b	17.6 c	45.0 c	15.7 d	0.671 c	7.71 c	0.058 d
ANOVA (p > F)															
Manure (M)	<0.001	<0.001	0.05	<0.001	0.27	0.003	<0.001	<0.001	<0.001	<0.001	<0.001	0.002	<0.001	<0.001	0.56
Length (L)	<0.001	<0.001	0.55	<0.001	0.005	<0.001	0.002	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
M × L	<0.001	<0.001	0.07	<0.001	<0.001	<0.001	<0.001	0.18	<0.001	<0.001	0.002	<0.001	<0.001	0.04	0.10

[a] All values are in mg L^{-1} except for EC (dS m^{-1}), pH, and sediment content (%). Within the same column, values followed by different letters are significantly different at the 0.05 probability level based on the LSD test.

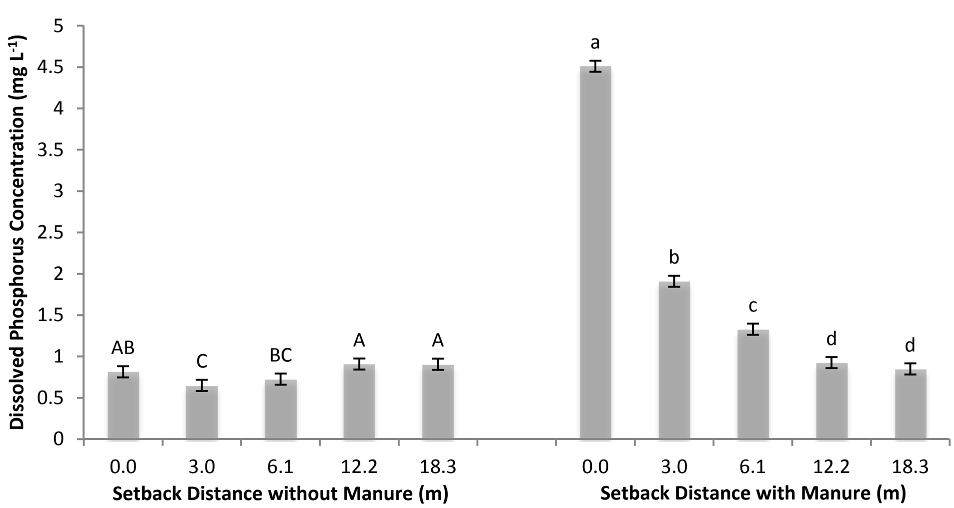

Figure 2. Dissolved phosphorus concentration as affected by setback distance for conditions with and without manure. Vertical bars are standard errors. Concentration values with different letters for conditions with or without manure are significantly different at the 0.05 probability level based on the LSD test.

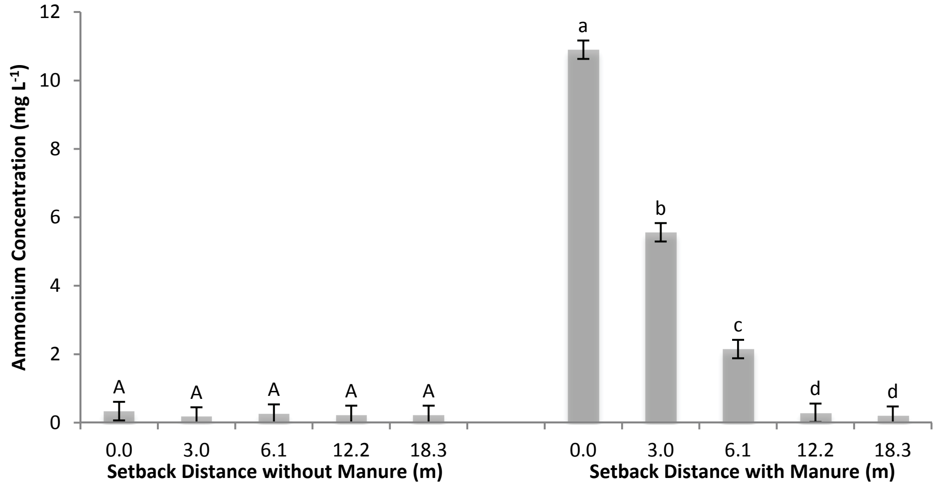

Figure 3. Ammonium concentration as affected by setback distance for conditions with and without manure. Vertical bars are standard errors. Concentration values with different letters for conditions with or without manure are significantly different at the 0.05 probability level based on the LSD test.

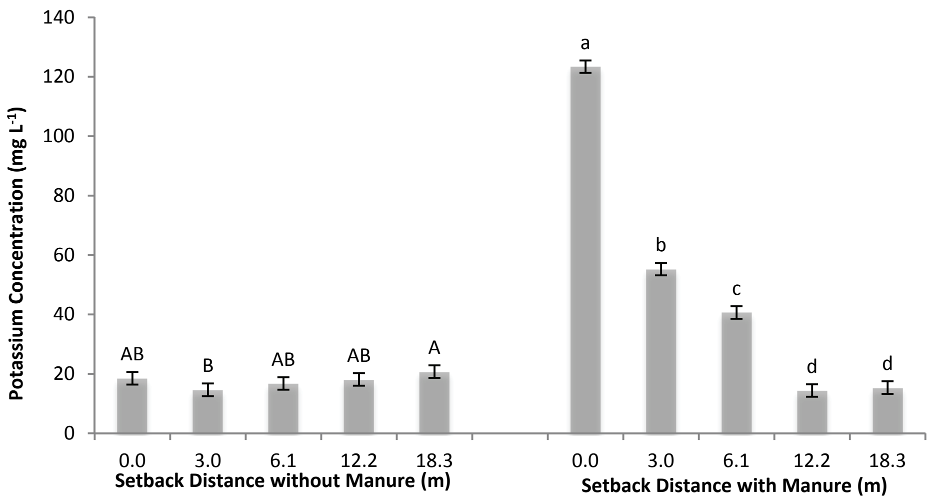

Figure 4. Potassium concentration as affected by setback distance for conditions with and without manure. Vertical bars are standard errors. Concentration values with different letters for conditions with or without manure are significantly different at the 0.05 probability level based on the LSD test.

the rainfall simulation tests were initiated, the manure that was applied soon became saturated. Rapid consumption of NO_3-N under anoxic conditions may then have occurred on the manure treatments, resulting in lower NO_3-N concentrations in runoff.

The existence of large concentrations of chloride is sometimes used to indicate the presence of manure. The concentration of chloride measured on the manure treatment was 11.0 mg L^{-1}, which was significantly greater than the 4.4 mg L^{-1} obtained on the no-manure treatment. Setback distance significantly influenced chloride concentrations in the runoff, with values decreasing from 10.9 to 3.6 mg L^{-1} as setback distance increased from 0.0 to 12.2 m.

The 8.83 Mg ha^{-1} of vegetative material present at the study site at the time of the field tests provided a substantial surface cover. A no-till management system had been established at the study site for several years. The sediment content of runoff on both the manure and no-manure treatments was minimal because of the large vegetative cover and no-till management.

The regression coefficients and coefficients of determination obtained when values for selected water quality constituents obtained on the manure treatments were substituted into equation 1 are shown in table 2. It can be seen from table 2 that the first-order exponential decay model shown in equation 1 can be used to provide reliable estimates of setback distance for the constituent values measured in this investigation.

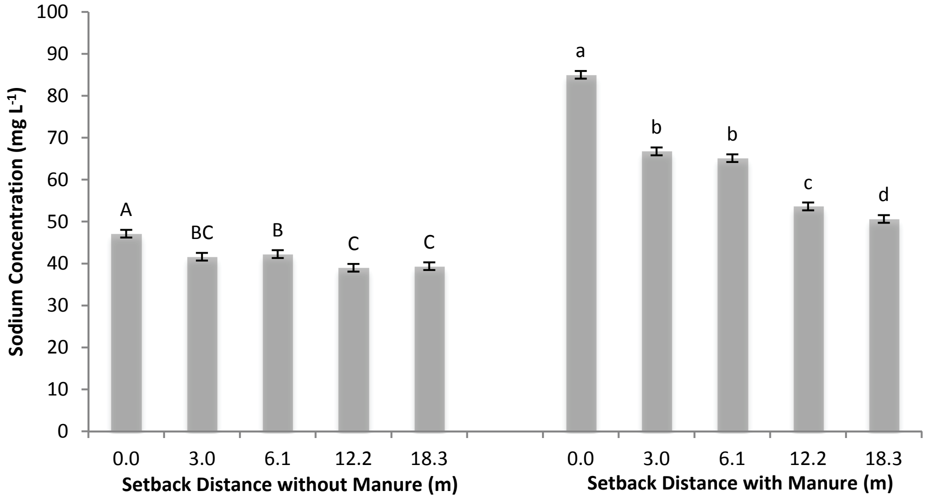

Figure 5. Sodium concentration as affected by setback distance for conditions with and without manure. Vertical bars are standard errors. Concentration values with different letters for conditions with or without manure are significantly different at the 0.05 probability level based on the LSD test.

Table 2. First-order decay model relating the change in water quality parameter (*y*) to setback distance (*x*, m) for the plots on which manure was applied.

Water Quality Parameter ($mg\ L^{-1}$)	Equation	R^2
DP	$y = 2.97e^{-0.082x}$	0.79
TP	$y = 4.53e^{-0.097x}$	0.85
NO_3-N	NS[a]	-
NH_4-N	$y = 9.64e^{-0.233x}$	0.95
TN	NS[a]	0.83
Boron	$y = 0.200e^{-0.103x}$	0.77
Calcium	$y = 86.4e^{-0.014x}$	0.63
Chloride	$y = 45.8e^{-0.103x}$	0.85
Magnesium	$y = 22.7e^{-0.021x}$	0.92
Potassium	$y = 89.8e^{-0.115x}$	0.87
Sodium	$y = 77.8e^{-0.026x}$	0.89
Sulfate	$y = 29.0e^{-0.038x}$	0.90
EC ($dS\ m^{-1}$)	$y = 1.22e^{-0.035x}$	0.93

[a] Not significant ($p > 0.05$).

Srivastava et al. (1996) and Lim et al. (1998) examined the effects of VFS width on the removal of selected constituents in runoff from fescue plots amended with poultry litter and beef cattle manure, respectively. Pollutant concentrations in runoff demonstrated a first-order exponential decline with increasing VFS width, with the exception of NO_3-N. The relationships among pollutant concentrations and setback distances obtained in the present investigation were also well represented by first-order exponential decay functions.

Lim et al. (1998) applied cattle manure at a rate of 60 kg N ha^{-1} to represent the amount of manure produced on a pasture from a stocking density of nine 450 kg animal units ha^{-1} for a seven-day grazing duration. In the present study, 378 kg N ha^{-1} was applied to meet the annual N requirement for corn (151 kg N ha^{-1} $year^{-1}$ for an expected yield of 9.4 Mg ha^{-1}). A rainfall intensity of 100 mm h^{-1} was used by Lim et al. (1998), while the simulator employed in the present investigation applied rainfall at a rate of 52 mm h^{-1}. The P content of the cattle manure applied by Lim et al. (1998) was 0.58%, which was similar to the 0.69% P content of the manure used in the present investigation.

The TP concentration of runoff exiting the application area where cattle manure was applied by Lim et al (1998) was 1.42 mg L^{-1}. In the present study, a runoff TP concentration of 6.31 mg L^{-1} was measured. Larger TP concentrations would be expected in the present study because a greater amount of manure was applied. VFS widths of 6.1, 12.2, and 18.3 m were found by Lim et al. (1998) to reduce concentrations of TP by 78%, 89%, and 84%, respectively. In the present study, reductions in TP concentrations of of 68%, 84%, and 83% were measured at setback distances of 6.1, 12.2, and 18.3 m, respectively. The regression coefficient (k) in equation 1 was reported by Lim et al. (1998) to be 0.09 and 0.10 for PO_4-P and TP, respectively. In the present investigation, k values of 0.08 and 0.10 were obtained for DP and TP, respectively. Thus, the rate of exponential decay of P in runoff as affected by VFS width and setback distance length was similar in these two studies.

Measurements of Mass Transport Rates

An interaction in measured mass transport rates between manure application and setback distance was found for DP, TP, NH_4-N, boron, magnesium, and potassium (table 3). For the water quality constituents for which interaction effects were found, changes in mass transport rates, in general, were minimal among setback distances on the treatments without manure (figs. 6 to 8). In contrast, significant reductions in mass transport values were found among setback distances, with mass transport values generally decreasing as setback distance increased. As an example, mass transport rates of DP on the treatments containing manure decreased by 59% as setback distance increased from 0 to 12.2 m (fig. 6). A setback distance of 12.2 m effectively reduced mass transport rates of DP, NH_4-N, and potassium to values similar to those obtained on the no-manure treatments (figs. 6 to 8).

Table 3. Effects of manure application and setback distance on transport values averaged over two rainfall simulation runs.[a]

	DP	TP	NO_3-N	NH_4-N	TN	Boron	Calcium	Chloride	Magne-sium	Potas-sium	Sodium	Sulfate	Soil Loss
Manure application													
No manure	3.39 b	3.85 b	85.5	0.979 b	119	0.204 b	301	19.1 b	82.0	74.6 b	181 b	78.4	4.31
Manure	6.49 a	8.86 a	75.5	4.89 a	138	0.367 a	335	48.0 a	99.4	147 a	315 a	109	5.09
Setback distance (m)													
0.0	4.21	5.48	50.8 b	3.52 ab	94.2 b	0.263 b	163 b	25.3 bc	55.5 b	106	187	70.8	4.47
3.0	5.80	7.30	89.8 a	4.34 a	150 a	0.446 a	421 a	45.3 a	107 a	141	281	112	7.12
6.1	4.28	5.61	77.7 ab	2.43 bc	128 a	0.286 b	342 a	33.7 ab	102 a	106	234	99.2	5.31
12.2	4.37	5.18	91.1 a	1.86 c	132 a	0.171 c	360 a	18.0 c	92.6 a	80.6	251	92.3	4.10
18.3	4.94	5.85	92.2 a	1.36 c	140 a	0.267 b	384 a	36.8 ab	97.2 a	99.6	219	94.8	3.26
ANOVA ($p > F$)													
Manure (M)	0.05	0.03	0.27	0.01	0.33	0.05	0.56	0.04	0.17	0.05	0.04	0.13	0.36
Length (L)	0.59	0.53	0.04	<0.001	0.04	0.006	<0.001	0.05	0.002	0.25	0.26	0.06	0.10
M × L	0.03	0.004	0.65	<0.001	0.19	0.02	0.09	0.17	0.04	0.004	0.62	0.13	0.50

[a] All values are in kg ha^{-1} min^{-1}. Within the same column, values followed by different letters are significantly different at the 0.05 probability level based on the LSD test.

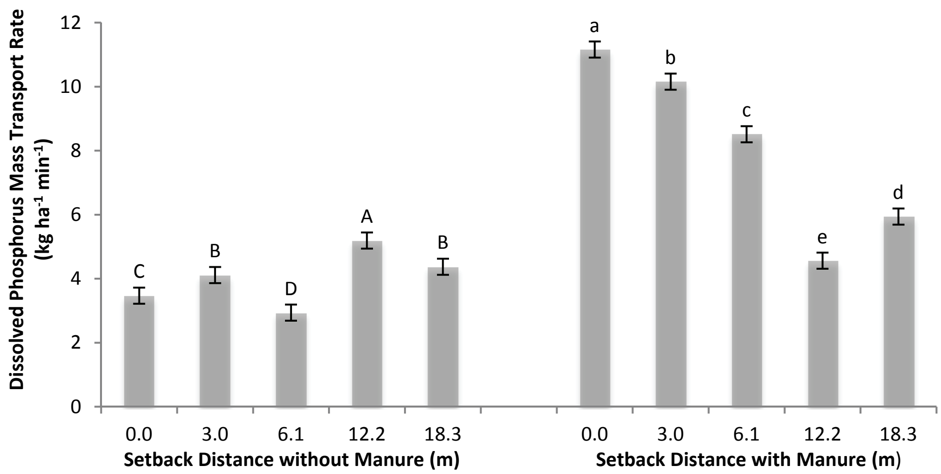

Figure 6. Dissolved phosphorus mass transport rate as affected by setback distance for conditions with and without manure. Vertical bars are standard errors. Mass transport rate values with different letters for conditions with or without manure are significantly different at the 0.05 probability level based on the LSD test.

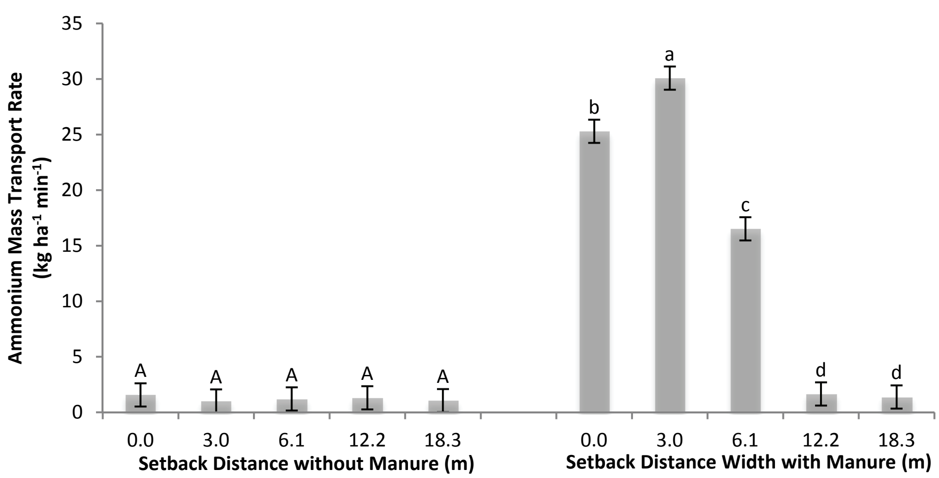

Figure 7. Ammonium mass transport rate as affected by setback distance for conditions with and without manure. Vertical bars are standard errors. Mass transport rate values with different letters for conditions with or without manure are significantly different at the 0.05 probability level based on the LSD test.

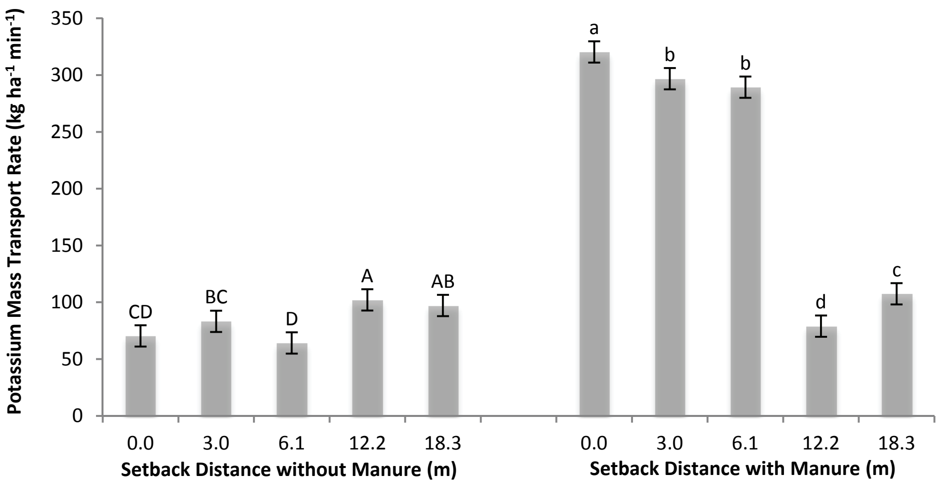

Figure 8. Potassium mass transport rate as affected by setback distance for conditions with and without manure. Vertical bars are standard errors. Mass transport rate values with different letters for conditions with or without manure are significantly different at the 0.05 probability level based on the LSD test.

Mass transport rates for chloride, potassium, and sodium were significantly greater on the manure treatments than the no-manure treatments. Setback distances significantly influenced mass transport rates for NO_3-N, TN, calcium, and chloride (table 3), but no significant differences in mass transport rates for these constituents were found for setback distances varying from 3.0 to 18.3 m. The regression coefficients and coefficients of determination obtained when values for selected water quality constituents on the manure treatments were substituted into equation 2 are shown in table 4. Variations in mass transport rates among setback distances were not significant for selected constituents, or the R^2 values obtained during the regression analysis did not indicate a good fit. It can be seen from table 4 that the first-order exponential decay model shown in equation 2 can be used to provide reliable estimates of the effects of setback distance on selected mass transport values measured in this investigation. The mass transport equations that are presented were derived for the given rainfall and experimental conditions, and they are not applicable for other rainfall rates.

The effects of VFS width on the mass transport of selected constituents in runoff from fescue plots amended with poultry litter and beef cattle manure were examined by Srivastava et al. (1996) and Lim et al. (1998), respectively. Mass transport was represented by a first-order exponential decline with increasing VFS width, with the exception of NO_3-N. First-order exponential decay functions obtained in the present study also provided reliable estimates of the effects of setback distance on mass transport rates of selected manure constituents.

Table 4. First-order decay model relating the change in transport parameter (*y*) to setback distance (*x*, m) for the plots on which manure was applied.

Water Quality Parameter ($kg\ ha^{-1}\ min^{-1}$)	Equation	R^2
DP	$y = 10.8e^{-0.044x}$	0.73
TP	$y = 16.9e^{-0.06x}$	0.73
NO_3-N	NS[a]	-
NH_4-N	$y = 36.2e^{-0.194x}$	0.89
TN	NS[a]	-
Boron	$y = 0.698e^{-0.061x}$	0.56
Calcium	NS[a]	-
Chloride	NS[a]	-
Magnesium	NS[a]	-
Potassium	$y = 347e^{-0.078x}$	0.75
Sodium	NS[a]	-
Sulfate	NS[a]	-

[a] Not significant ($p > 0.05$).

RUNOFF CHARACTERISTICS AS AFFECTED BY INFLOW *Concentration Measurements*

Under normal field conditions, the upslope area on which manure is applied is much greater than the 4.9 m examined in this investigation. Therefore, additional flow was introduced at the top of the plots to simulate a greater upslope contributing area. Rainfall intensity and duration are both highly variable. By relating concentration measurements to flow rate, the experimental results would be applicable to a much larger range of rainfall and runoff conditions.

A three-way interaction in concentration values among manure application, setback distance, and inflow rate was found for each of the measured constituents except NO_3-N, boron, chloride, and sediment content (table 5). The effects of flow rate on potassium concentration for the manure treatments are shown in figure 9. The results obtained for potassium are characteristic of the other constituents for which three-way interactions were found. Beef cattle manure was applied to the entire 4.9 m area upslope from the 0 m sampling location. As inflow was introduced at the top of the plot, the potassium concentration at the bottom of the manure application area (0 m setback distance) consistently decreased as a result of dilution.

For a given flow rate, concentration values, in general, decreased as setback distance became larger (fig. 9). As an example, at a flow rate of 87.6 L min^{-1}, the concentration of potassium decreased from 51.5 to 25.5 mg L^{-1} as setback distance increased from 3.0 to 23.1 m. For a given setback dis-

Table 5. Effects of manure application, setback distance, and inflow on water quality parameters.[a]

	DP	TP	NO_3-N	NH_4-N	TN	Boron	Calcium	Chloride	Magne-sium	Potas-sium	Sodium	Sulfate	EC	PH	Sediment Content
Manure application															
No manure	0.646 b	0.729 b	14.9	0.180 b	20.3 b	0.048 b	69.1	6.17 b	17.0 b	14.1 b	49.3 b	15.6 b	0.704 b	8.34 a	0.103
Manure	2.43 a	2.94 a	15.3	2.19 a	25.1 a	0.100 a	67.6	14.0 a	18.0 a	43.9 a	62.6 a	19.3 a	0.870 a	8.18 a	0.107
Setback distance (m)															
0.0	2.14 a	2.64 a	14.6	1.91 a	25.8 a	0.098 a	63.6 c	14.3	18.6 a	49.0 a	61.7 a	18.7 a	0.868 a	8.18 b	0.140 a
3.0	1.77 b	2.11 b	14.8	1.76 ab	21.7 b	0.089 a	66.7 b	6.20	17.6 ab	28.8 b	55.4 b	17.1 b	0.778 bc	8.22 b	0.116 ab
6.1	1.69 b	1.95 b	16.6	1.46 b	22.6 b	0.078 a	71.5 a	11.6	17.6 ab	26.4 bc	56.7 b	18.7 a	0.804 b	8.22 b	0.107 bc
12.2	1.16 c	1.39 c	14.7	0.595 c	21.9 b	0.044 b	71.0 a	6.80	17.0 b	21.9 cd	53.8 bc	16.5 b	0.750 cd	8.35 a	0.086 c
18.3	0.923 d	1.08 d	14.7	0.206 c	21.4 b	0.052 b	69.0 ab	11.5	16.8 b	18.8 d	52.3 c	16.2 b	0.736 d	8.32 a	0.075 c
Inflow															
0	1.34 c	1.68 b	17.0 a	0.875 b	24.8 a	0.060 b	68.6 ab	11.2 ab	16.9 b	20.2	53.4 b	17.6 a	0.777 b	8.20 b	0.111 a
1	1.61 b	1.96 a	17.0 a	1.20 a	24.0 a	0.068 ab	69.5 a	13.4 a	17.4 ab	22.6	56.3 a	18.1 a	0.804 a	8.23 b	0.112 a
2	1.71 a	1.99 a	12.9 b	1.39 a	22.2 b	0.077 a	68.4 ab	8.50 bc	17.7 a	27.1	57.5 a	17.7 a	0.803 a	8.30 a	0.094 b
3	1.50 bc	1.71 b	13.5 b	1.28 a	19.7 c	0.073 a	66.8 b	7.16 c	18.0 a	23.2	56.7 a	16.4 b	0.764 b	8.30 a	0.102 ab
ANOVA (p > F)															
Manure (M)	<0.001	<0.001	0.69	0.002	0.003	0.002	0.26	0.05	0.03	<0.001	<0.001	<0.001	<0.001	0.03	0.64
Length (L)	<0.001	<0.001	0.76	0.002	<0.001	<0.001	<0.001	0.07	0.004	<0.001	<0.001	<0.001	<0.001	0.03	0.002
Inflow (I)	<0.001	<0.001	<0.001	<0.001	<0.001	0.007	0.05	0.04	0.001	0.08	<0.001	<0.001	<0.001	0.001	0.02
M × L	<0.001	<0.001	0.13	0.002	<0.001	<0.001	<0.001	0.74	0.73	<0.001	0.009	<0.001	<0.001	0.12	0.20
M × I	<0.001	<0.001	0.97	<0.001	<0.001	0.25	<0.001	0.001	0.46	0.009	0.008	<0.001	0.007	0.08	0.68
L × I	<0.001	<0.001	0.30	<0.001	<0.001	0.43	0.01	0.53	0.15	<0.001	0.005	0.006	<0.001	0.11	0.45
M × L × I	<0.001	<0.001	0.06	<0.001	<0.001	0.40	<0.001	0.22	0.04	<0.001	0.001	<0.001	<0.001	0.04	0.88

[a] All values are in mg L^{-1} except for EC (dS m^{-1}), pH, and sediment content (%). Within the same column, values followed by different letters are significantly different at the 0.05 probability level based on the LSD test.

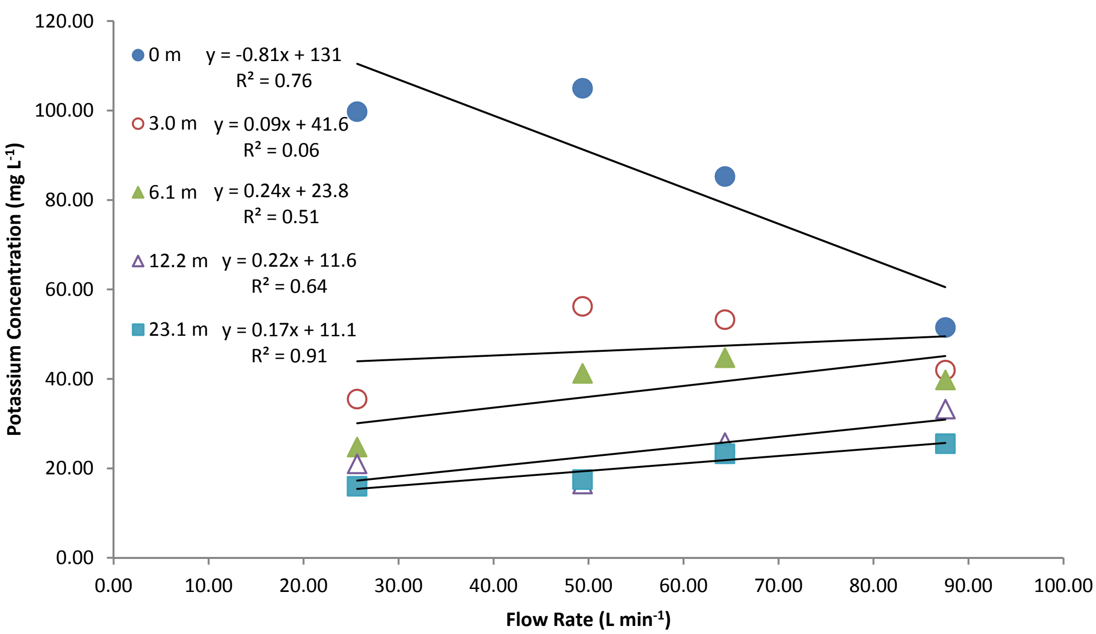

Figure 9. Potassium concentration as affected by flow rate for the manure treatments.

tance, a small increase in potassium concentration was generally found as flow rate increased for setback distances varying from 3.0 to 23.1 m.

An experiment to determine how the quality of runoff treated with poultry litter was impacted by litter application rate and rainfall intensity for storms occurring one day after application was conducted by Edwards and Daniel (1993). The experimental plots were 1.5 wide by 6.0 m long. Concentrations of DP, TP, total Kjeldahl nitrogen, and chemical oxygen demand decreased with increasing rainfall intensity because of the dilution resulting from additional runoff.

Measurements of Mass Transport Rates

A three-way interaction in mass transport rates among manure application, setback distance, and inflow rate was found for DP, boron, and potassium (table 6). The effects of flow rate on mass transport rates for DP and potassium for the manure treatments are shown in figures 10 and 11.

At each setback distance, mass transport rates, in general, increased as flow rate increased (figs. 10 and 11). For a given flow rate, mass transport rates, in general, decreased as setback distance became larger. As an example, at a flow rate of 87.6 L min^{-1}, the mass transport rate for potassium decreased from 2054 to 306 kg ha^{-1} min^{-1} as setback distance increased from 3.0 to 23.1 m (fig. 11).

Thayer et al. (2012a, 2012b) measured the effects of varying beef cattle manure application rates and flow rates on nutrient loads in runoff. The size of the plots examined by

Table 6. Effects of manure application, setback distance, and inflow on transport parameters.[a]

	DP	TP	NO_3-N	NH_4-N	TN	Boron	Calcium	Chloride	Magne-sium	Potas-sium	Sodium	Sulfate	Soil Loss
Manure application													
No manure	7.78 b	9.04 b	187	2.28 b	268	0.704 b	962	56.3 b	244	175 b	698 b	207 b	13.3 b
Manure	35.1 a	44.6 a	202	35.5 a	340	1.76 a	906	172 a	257	670 a	883 a	266 a	17.6 a
Setback distance (m)													
0.0	33.2 a	46.5 a	240 a	36.8 a	430 a	2.15 a	1142 a	178 a	355 a	827 a	1136 a	335 a	23.9 a
3.0	27.6 ab	33.4 b	219 ab	26.2 a	340 b	1.60 b	1082 ab	83.1 b	292 ab	470 b	915 b	272 ab	17.7 ab
6.1	24.1 b	27.4 c	205 ab	21.8 ab	297 bc	1.30 b	957 bc	149 a	243 bc	367 bc	756 bc	237 bc	14.5 ab
12.2	14.0 c	16.9 d	175 bc	7.6 bc	260 c	0.684 c	859 c	73.1 b	207 cd	275 cd	662 cd	191 cd	9.85 b
18.3	8.46 c	10.0 e	133 c	1.9 c	193 d	0.505 c	630 d	86.9 b	154 d	174 d	485 d	148 d	11.3 b
Inflow													
0	6.59 d	8.7 d	90.0 c	3.8 c	132 d	0.369 d	369 d	60.9 b	92.5 d	155 d	287 d	29.2 d	7.3 c
1	19.2 c	25.0 c	193 b	18.9 b	279 c	1.13 c	786 c	136 a	201 c	386 c	638 c	209 c	14.2 b
2	27.8 b	34.0 b	205 b	25.0 ab	354 b	1.57 b	1069 b	133 a	286 b	527 b	925 b	276 b	16.5 b
3	32.3 a	39.8 a	289 a	27.6 a	450 a	1.92 a	1513 a	125 a	422 a	623 a	1312 a	372 a	23.9 a
ANOVA (p > F)													
Manure (M)	<0.001	<0.001	0.46	<0.001	0.003	0.001	0.38	0.02	0.50	0.001	0.004	0.006	0.05
Length (L)	<0.001	<0.001	0.02	<0.001	<0.001	<0.001	<0.001	0.01	<0.001	<0.001	<0.001	<0.001	0.002
Inflow (I)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	<0.001	<0.001	<0.001	<0.001	<0.001
M × L	<0.001	<0.001	0.51	<0.001	0.01	<0.001	0.84	0.06	0.75	<0.001	0.30	0.53	0.38
M × I	<0.001	<0.001	0.85	<0.001	0.02	<0.001	0.23	0.003	0.66	<0.001	0.12	0.16	0.54
L × I	<0.001	<0.001	0.07	<0.001	<0.001	<0.001	<0.001	0.61	<0.001	<0.001	<0.001	<0.001	<0.001
M × L × I	<0.001	0.19	0.30	0.31	0.43	0.03	0.84	0.73	0.93	<0.001	0.9	0.66	0.64

[a] All values are in kg ha^{-1} min^{-1}. Within the same column, values followed by different letters are significantly different at the 0.05 probability level based on the LSD test.

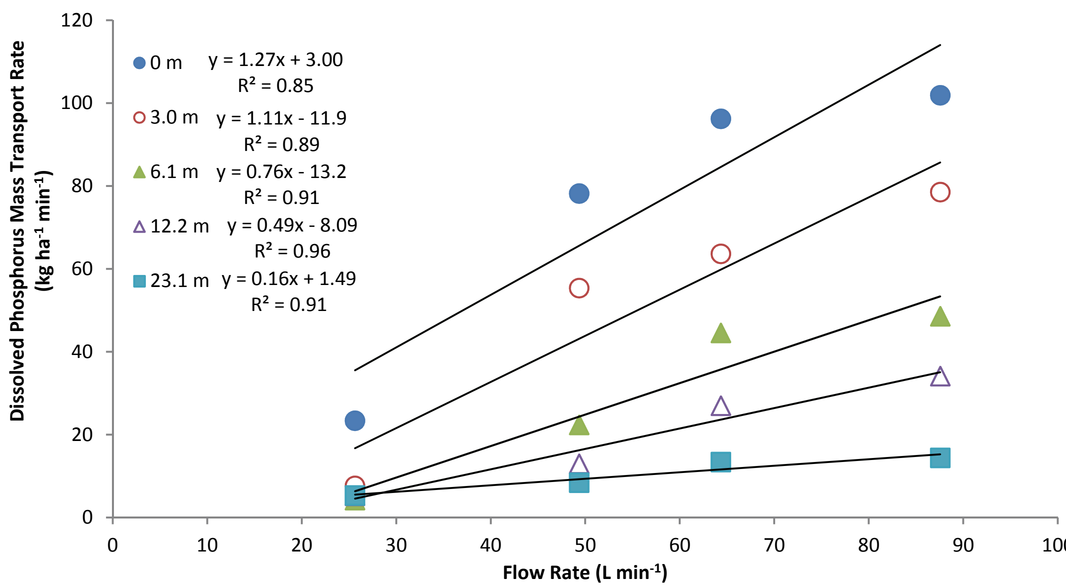

Figure 10. Dissolved phosphorus mass transport rate as affected by flow rate for the manure treatment.

Thayer et al. (2012a, 2012b) were 0.75 m wide by 2.0 or 4.0 m long, respectively. Mean runoff rates varied from 1.0 to 22.0 L min^{-1}. Each of the measured chemical constituents was significantly influenced by runoff rate, with values generally increasing as inflow rate increased.

Conclusions

A setback distance of 12.2 m effectively reduced the concentrations of DP, TP, NH_4-N, boron, calcium, magnesium, potassium, and sulfate in runoff from areas on which cattle manure had been applied to values similar to those obtained on the no-manure treatment. Mass transport rates of DP, TP, NH_4-N, boron, and potassium from the plots on which manure had been applied were also reduced to values similar to the no-manure treatment at a setback distance of 12.2 m.

A first-order exponential decay function provided estimates of the effects of setback distance on the concentrations and mass transport rates of selected constituents. For a given setback distance, mass transport rates of DP, boron, and potassium on the treatments with manure, in general, increased as flow rate increased. When appropriate setback distances were used, the transport of selected pollutants in runoff following land application of manure was effectively reduced.

The results obtained in this investigation are strictly applicable to the given experimental conditions. The rainfall simulation tests were performed on a no-till cropland site with a 6.2% slope gradient on which 8.84 Mg ha^{-1} of wheat and cover crop residue were present. Additional tests are needed to characterize the effectiveness of selected setback distances in removing pollutants in runoff from areas with

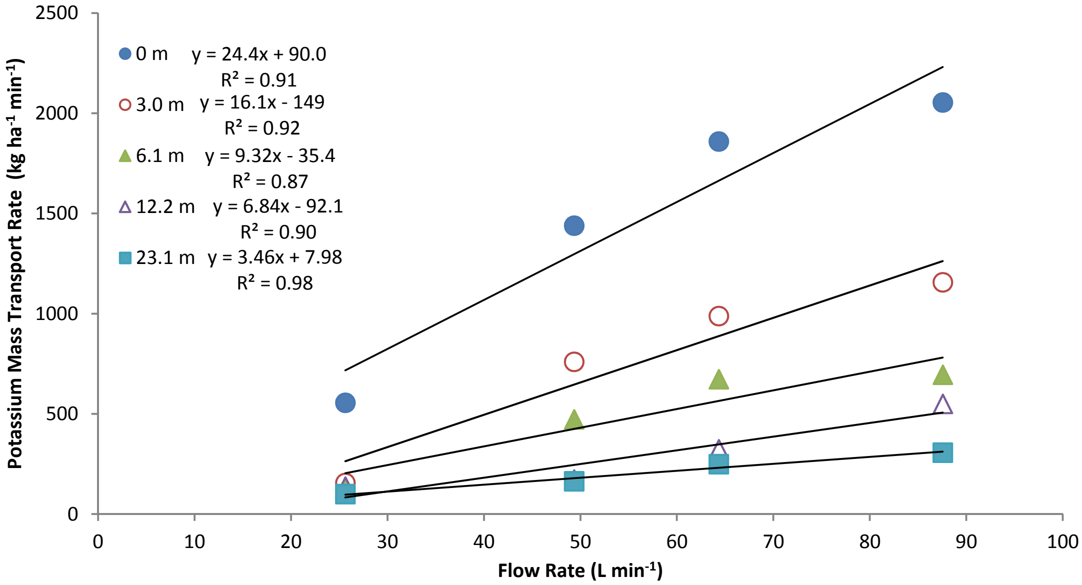

Figure 11. Potassium mass transport rate as affected by flow rate for the manure treatment.

different slopes, soils, management, and cropping conditions.

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